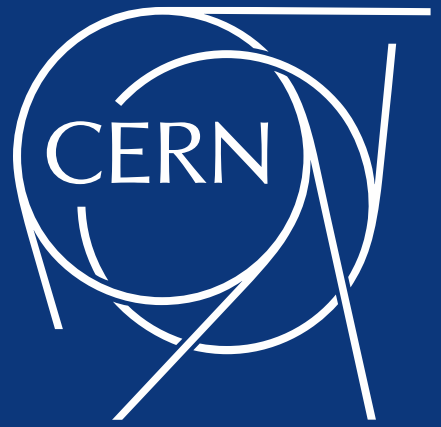


Status of the Accelerator

Matteo Solfaroli BE/OP

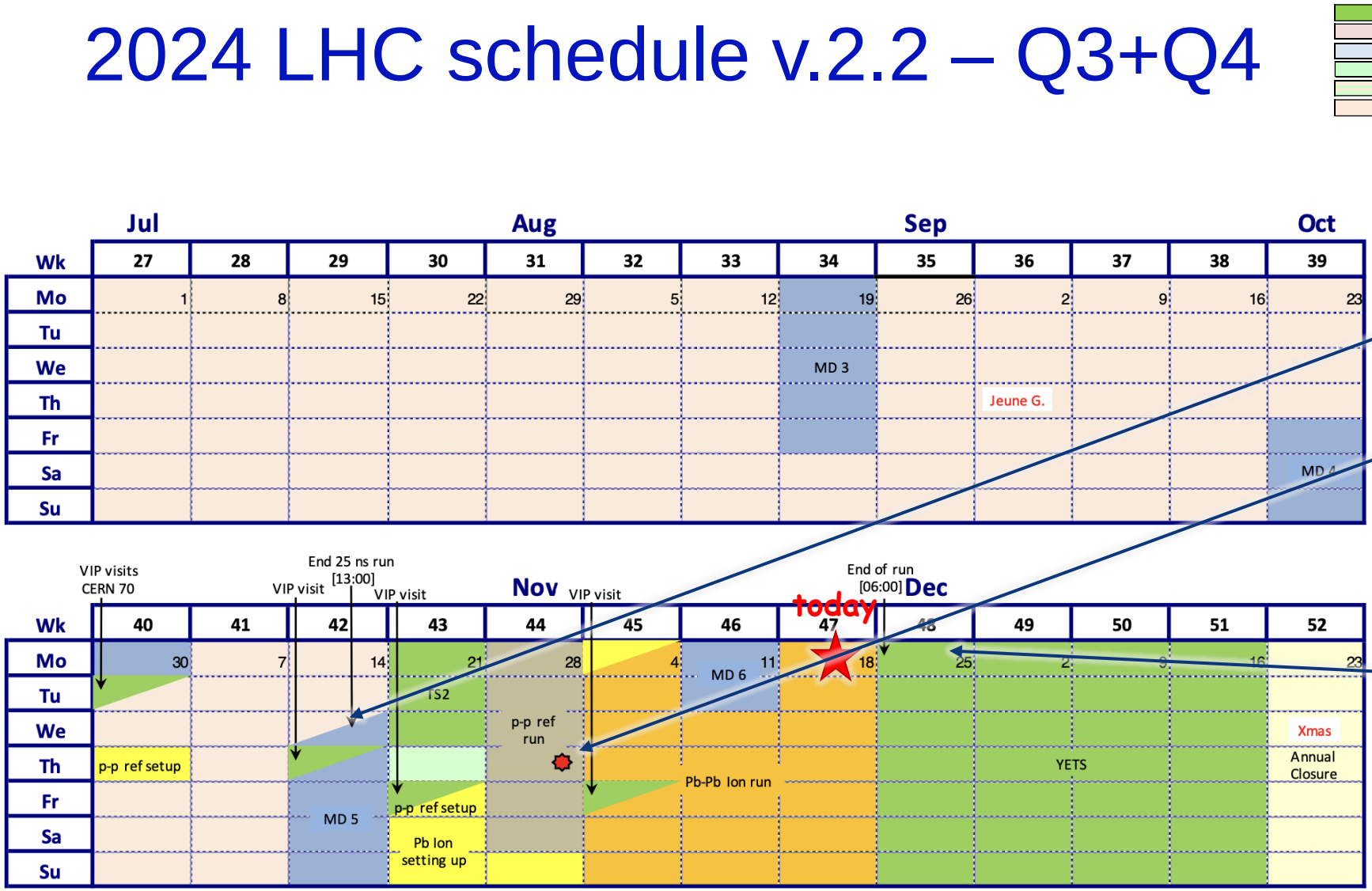
160th LHCC OPEN Session

Nov 18th, 2024

Outline

- **2024 run highlights**
  - low beta pp, pp ref run, IONS
- 2025 configuration
- 2025 schedule options

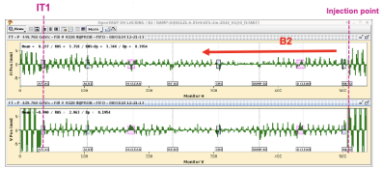
2024 LHC schedule v.2.2 – Q3+Q4



- 2024 low beta run **completed**
- 2024 pp reference run **completed**
- 2024 IONS run **ongoing**
- End of 2024 run on **Monday 25th November @6am**

LHC in 2024

First injection: 8th March (3 days early)

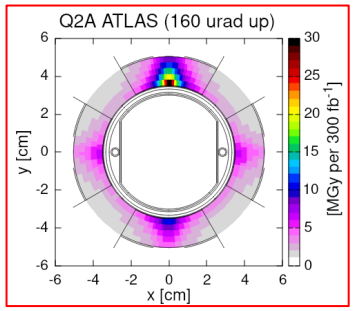


pp run

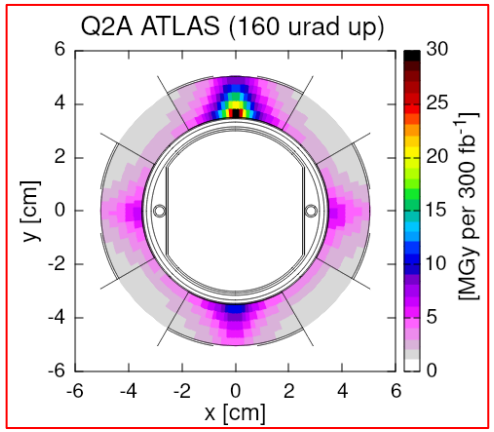
ref run IONS run

March | April | May | June | July | August | September | October | November

Reverse Polarity optics commissioned (~ +1 week)



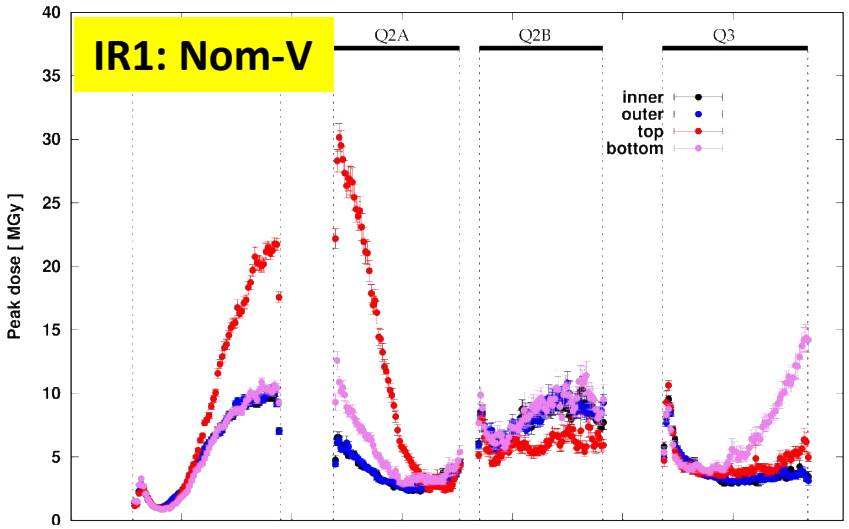
Reversed Polarity (RP) optics



The magnets in inner triplet regions see localised high dose rates due to collision debris, which can lead to damage and failure

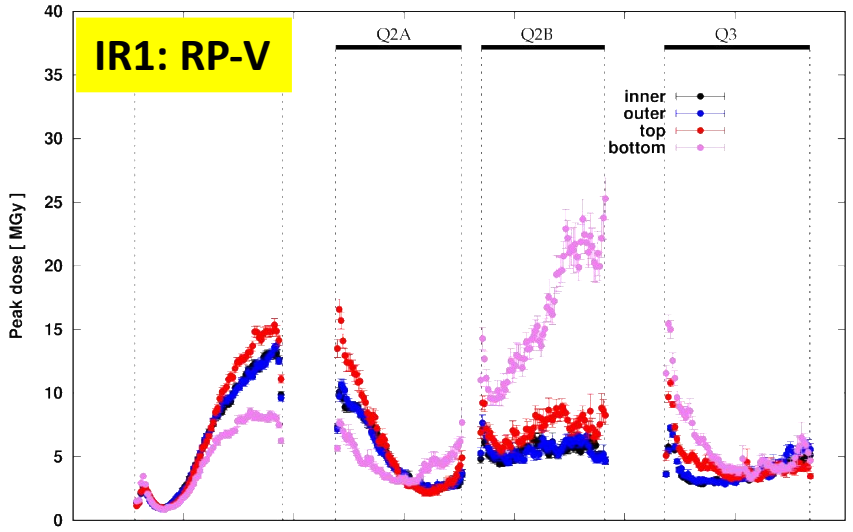
Local optics change to **redistribute the radiation**, allowing for longer lifetime of the equipment:

- **Implemented in P1** in 2024, as most critical



Peak dose distribution profile along the triplet region

Example for IP1



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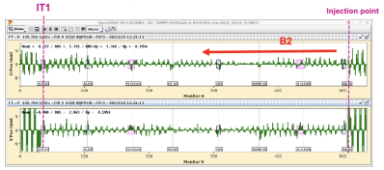
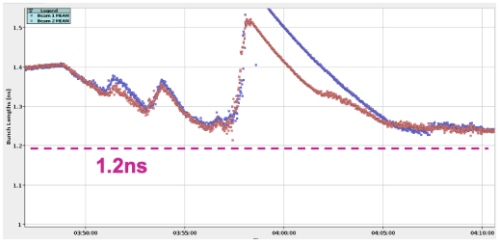


Bunch length control/target
Limit RF module heating risk



pp run | ref run | IONS run

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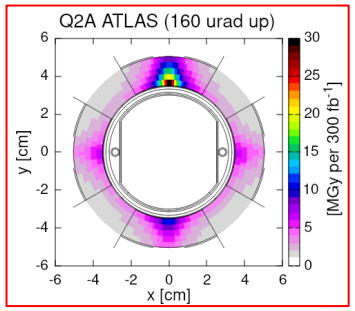
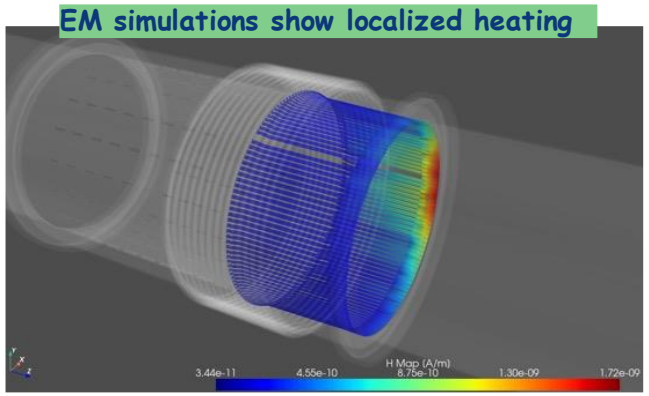


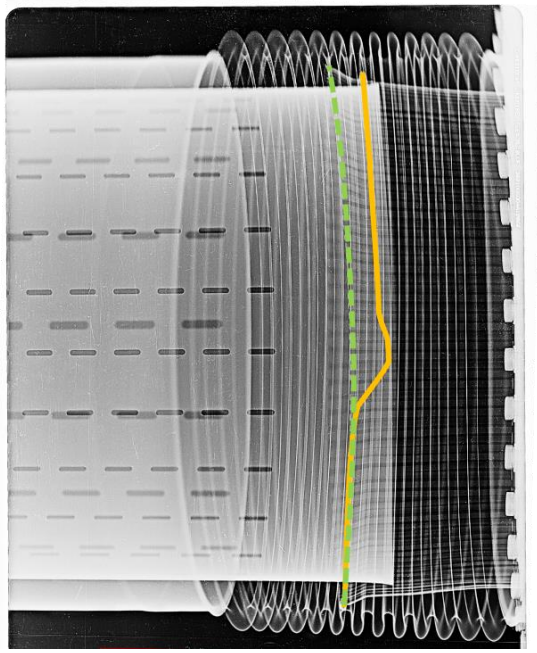
First Stable Beams @6.8 TeV 5th April (3 days early)

LHCb VELO closed for the 1st time

RF finger vacuum modules

VISUAL INSPECTION
annealed/plasticised spring on the 212 mm vacuum module due to localized temperature increase to more than 500°C





IMPACT in 2023

- ~5 days lost
- Bunch intensity limited to 1.6e^{11} p/b

- Difficult to identify **intensity limitation** (strong dependence on contact quality)
- **Simulations** to assess impact of beam parameters on power deposition

Consolidation plan:

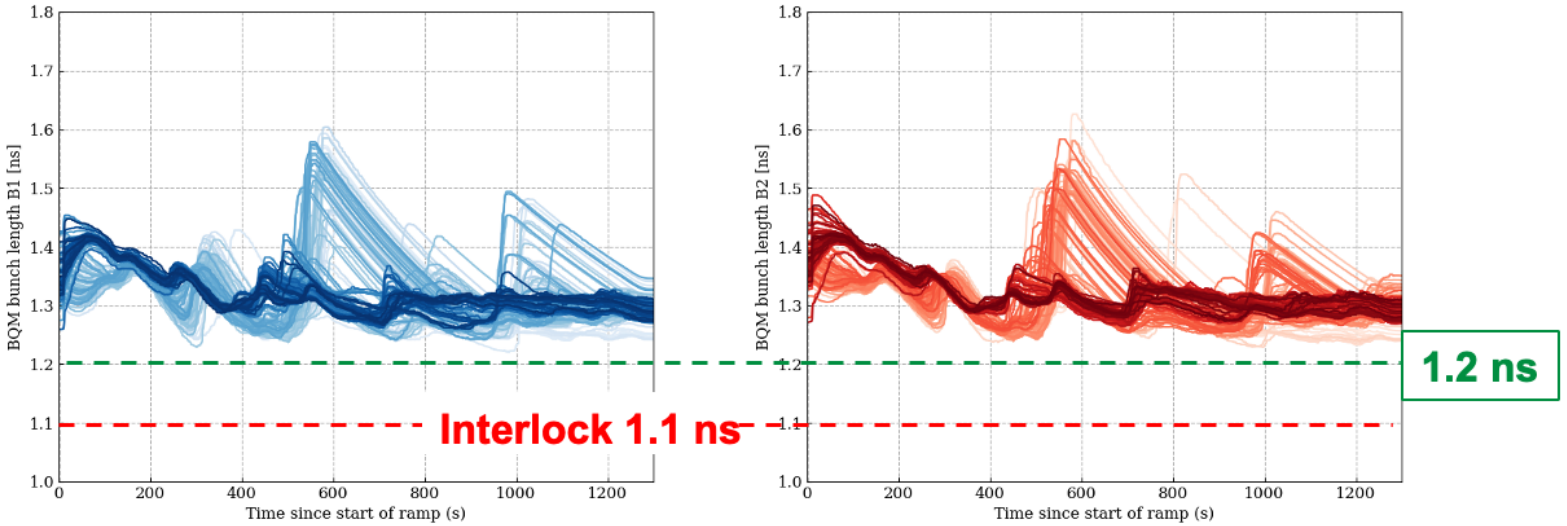
- 47 replaced during **23/24 EYETS**
- 24 foreseen in **24/25 YETS**
  - No failure expected with ideal contact

LMC 479: limit bunch intensity at 1.6e^{11} p/b, while maximizing the bunch length throughout the cycle

Improved control of bunch length provides a **safety factor** of ~2 or more in power deposition

Beam power and bunch length

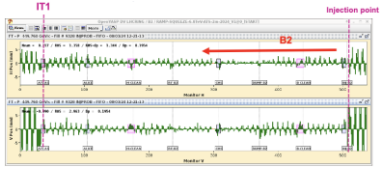
- **Longitudinal blow-up control** significantly improved
  - bunch lengths in the ramp **>1.25 ns,** compared to 1.1 ns in 2023
  - **Interlock** implemented at 1.1 ns, then moved to 1.2 ns
  - According to simulations, this lowers the beam power by **> factor 2**



This operational improvement together with the upcoming completion of the warm vacuum modules consolidation can open a **window for future higher intensity tests/operation,** without impacting availability

LHC in 2024

First injection: 8th March (3 days early)



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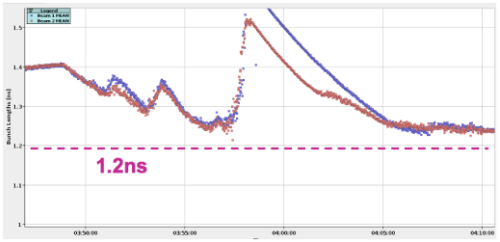

1200 bunches on 14th April (10 days early)

pp run | ref run | IONS run

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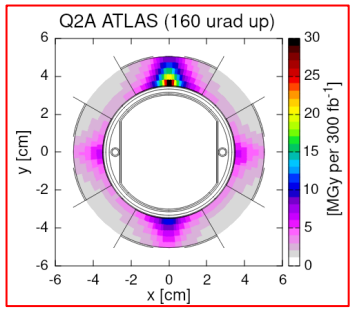

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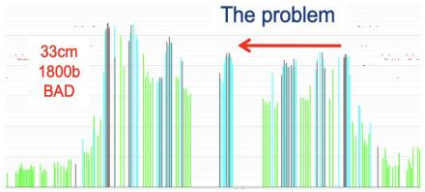

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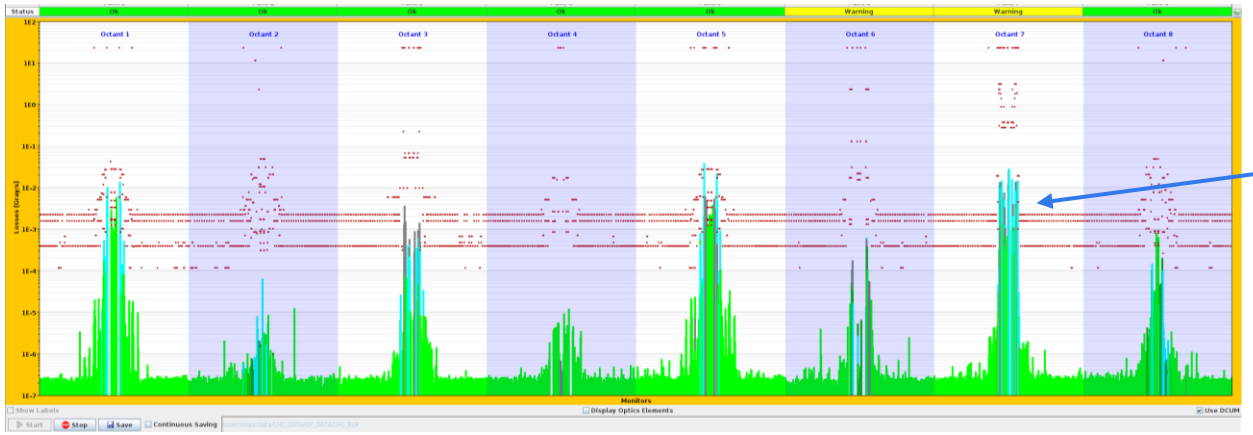

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LHC in 2024

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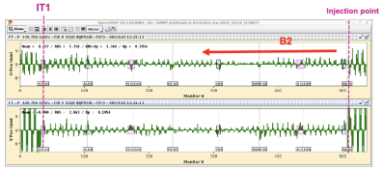

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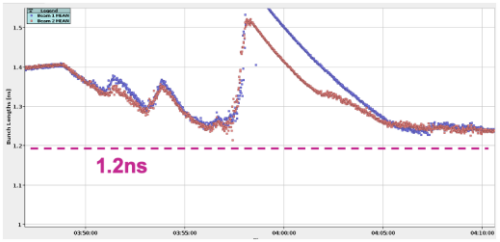

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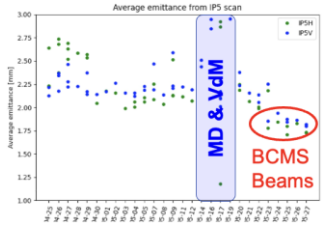
VdM & Calibration
Runs, 16 – 20 May

Availability	Stable beams (SB)
85.3%	63.6%

BCMS beams
May



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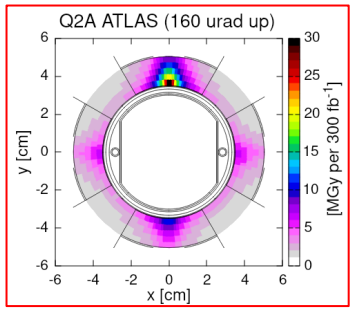

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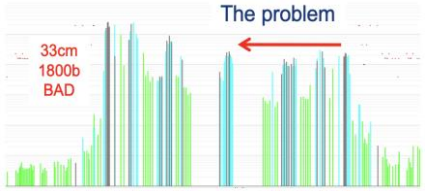
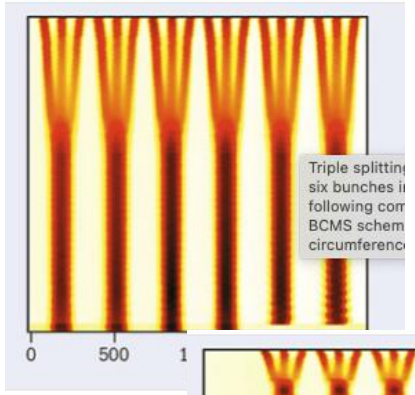
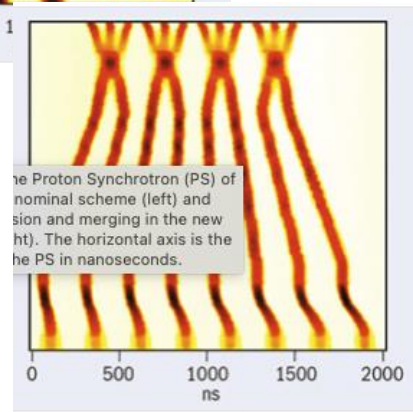


BCMS beam

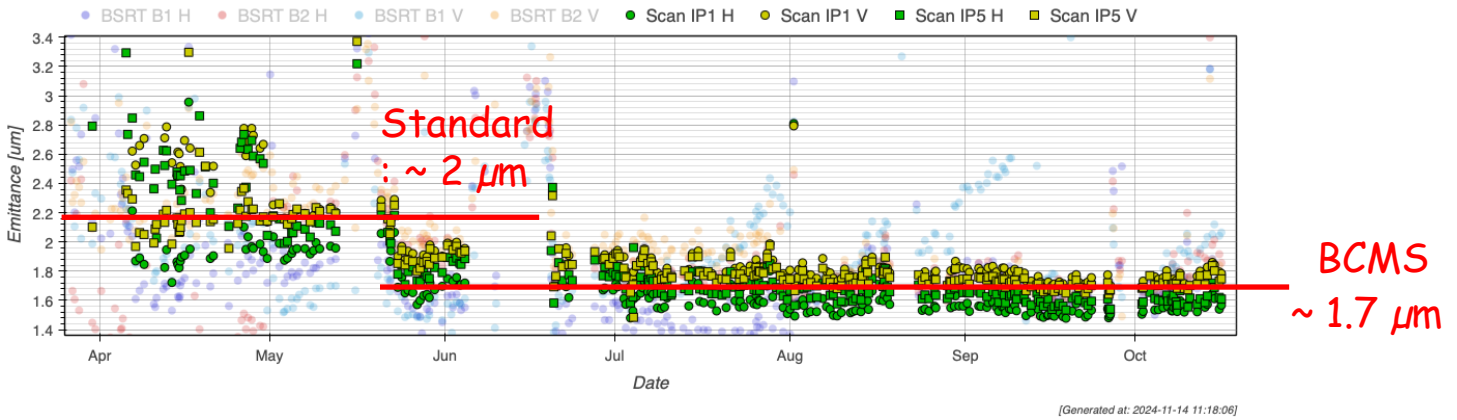
With a filling scheme based on 3x36b patterns, the **standard 25 ns** and Batch Compression and (bunch) Merging and (bunch) Splitting (**BCMS**) beams are **interchangeable** transparently

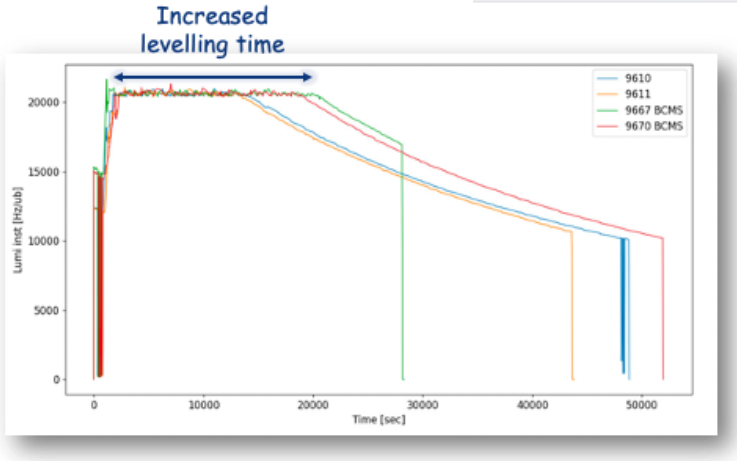




Optimized BCMS beams deployed in the LHC in May

- **Brightness** theoretical **10% higher**
- **Better equivalent cross-section** (provided emittance is preserved)
- Smaller emittance also beneficial for **losses reduction**, especially at injection





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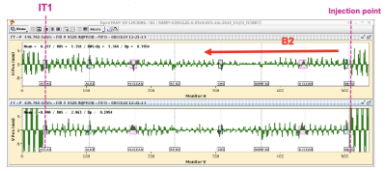

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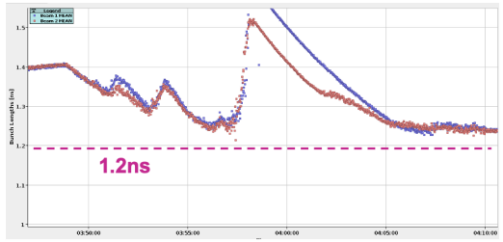

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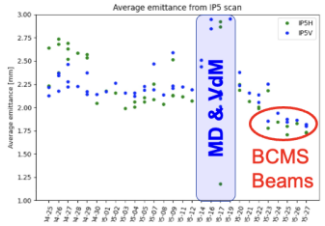

pp run — ref run — IONS run

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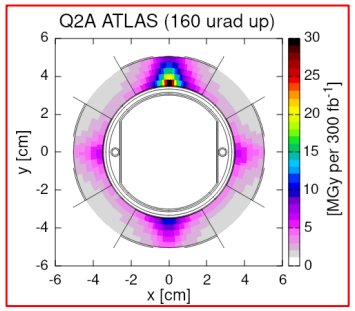

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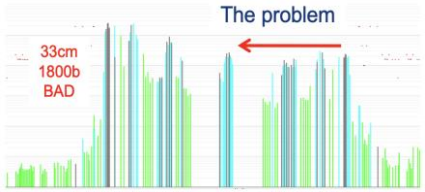
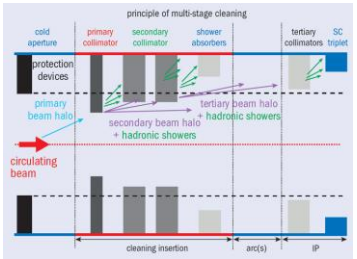


β* back to 30 cm 17th June



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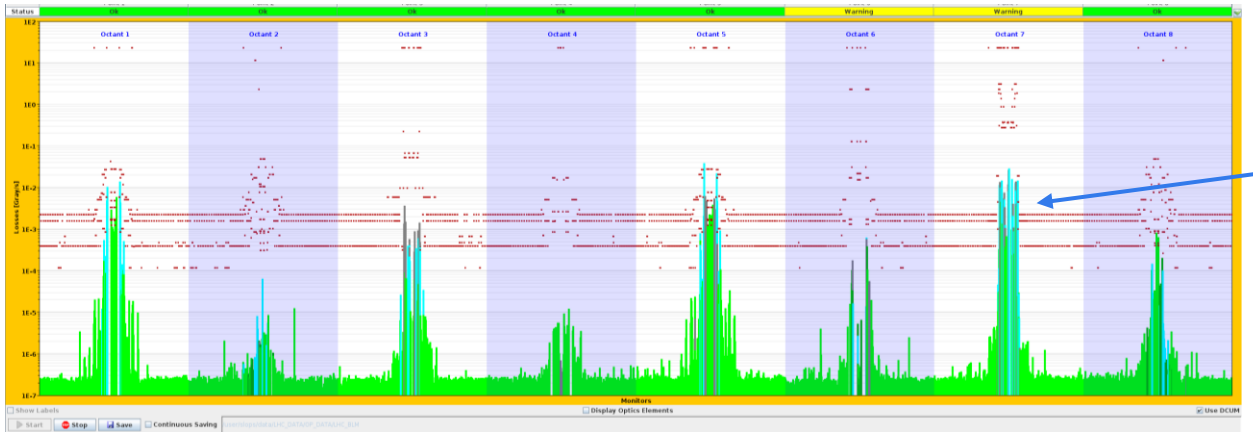

Highest losses in the **middle of insertion** (instead of extremities, where primary collimators are located)

- Broken hierarchy can compromise protection
- ➔ **limitation on beta*** (about 1-2% loss)

- Studies, tests and simulations indicated that losses are generated by **particles in the off-momentum halo** (not core of the beam)
- **Various mitigations** put in place to improve the behaviour
- Machine **re-validated after TS#1** with mitigations in place
- **Beta* limitation lifted**

LHC in 2024

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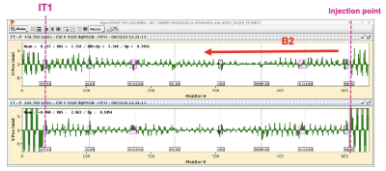

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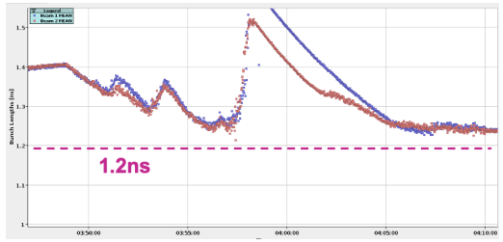

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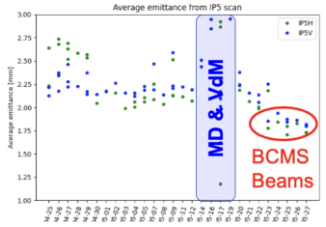
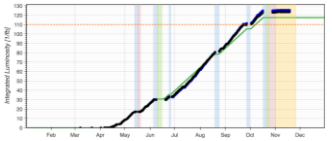


Stable Lumi Production Summer period



Beyond 110 fb^{-1}

pp run — ref run — IONS run

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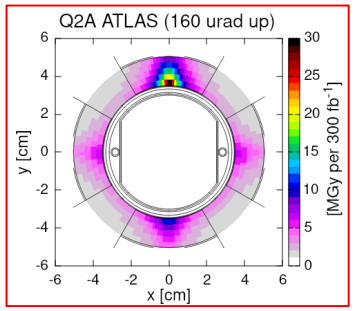

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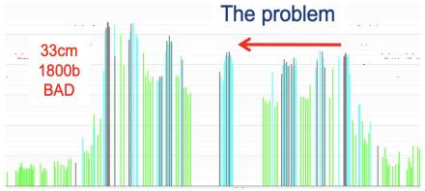

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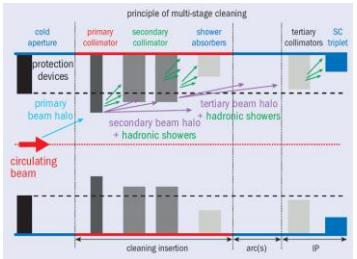
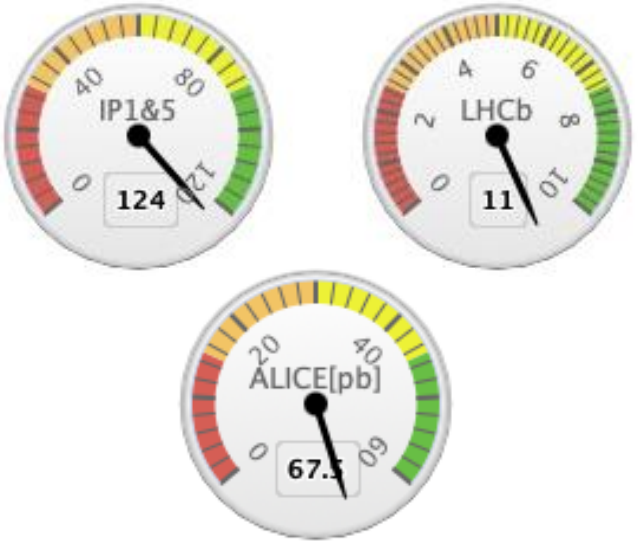
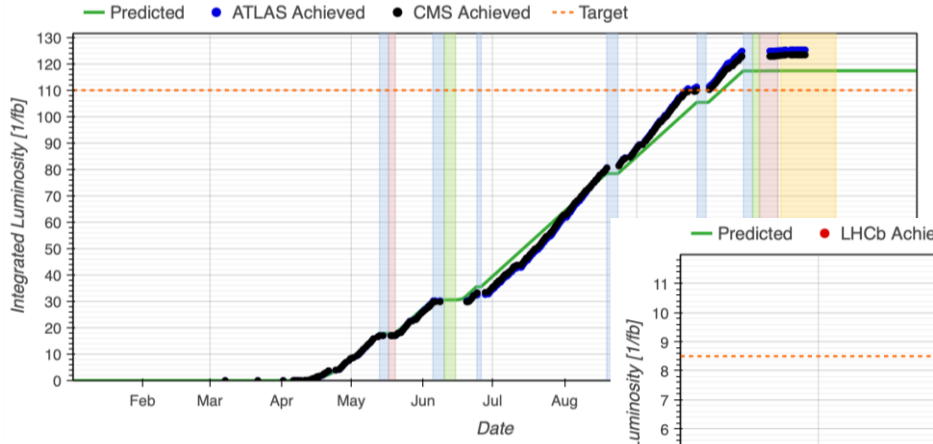
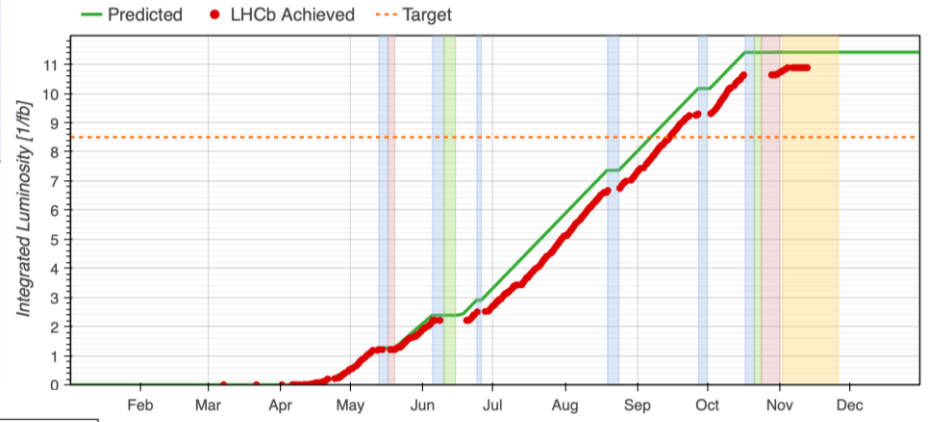


Production

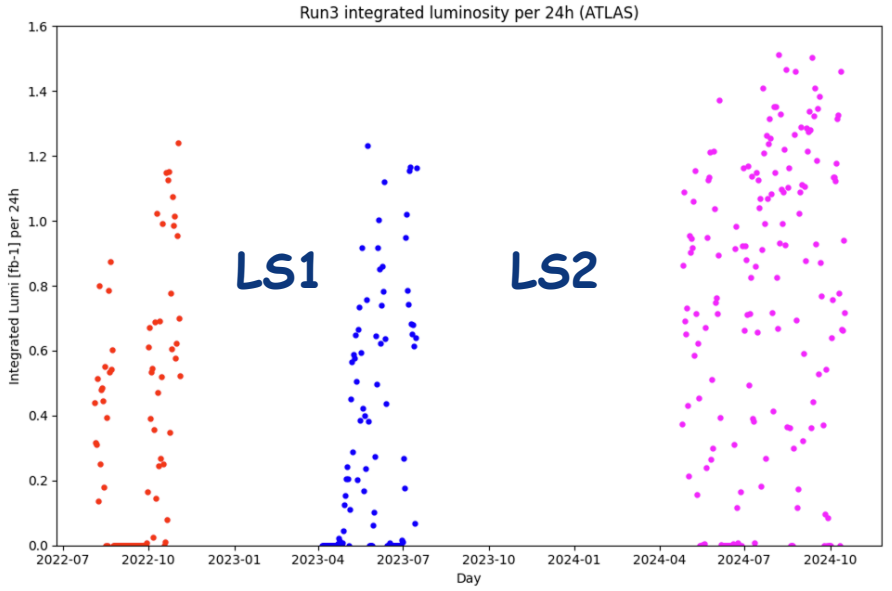
- **124 fb^{-1}** in ATLAS/CMS
- **11 fb^{-1}** in LHCb
- **67.5 pb^{-1}** in ALICE
- Highest production **rate ever**
- **Peak luminosity** at ~2.1e^{34} cm^{-1} s^{-1} (limited by cryogenic)

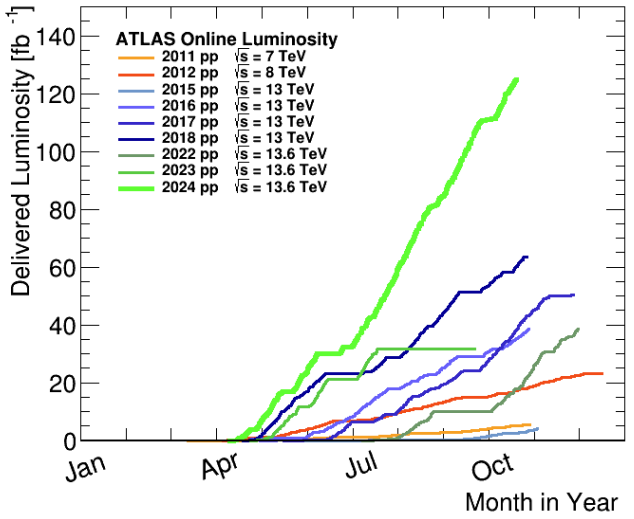






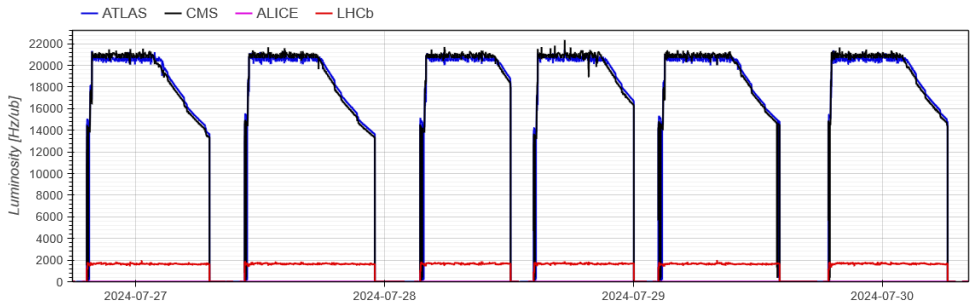
- **2024 AVG** rate = 0.83 fb^{-1}/24h
- **2024 highest** rate = 1.5 fb^{-1}/24h (midnight to midnight)

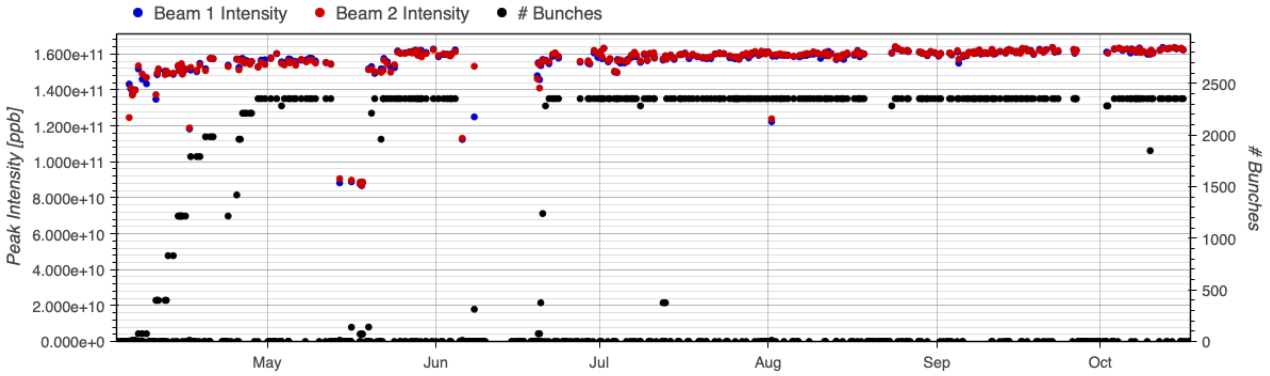




Production

- **Combined** (beta* + offset) **levelling** allowed for
  - **6-7 hours levelling** with BCMS beams
  - **Well balanced** luminosity between CMS and ATLAS
- LHCb levelled **through the entire fill**

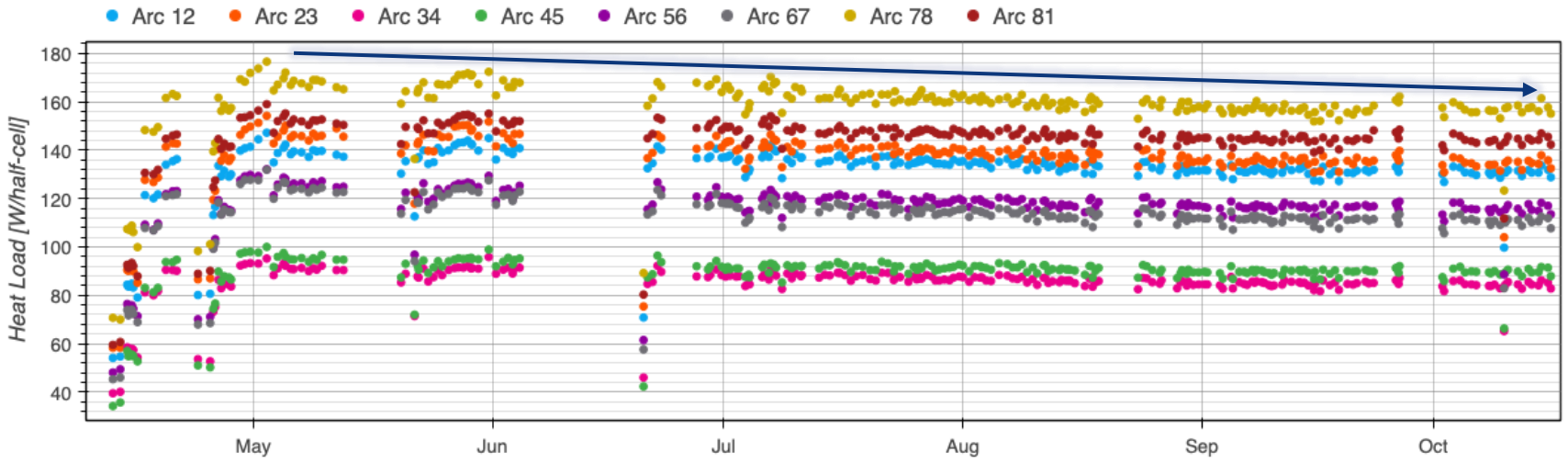




- Bunch intensities stable at **1.6e^{11} ppb** at start of stable beams
- **Stored energy ~410 MJ** / beam @6.8 TeV (~100 kg TNT)

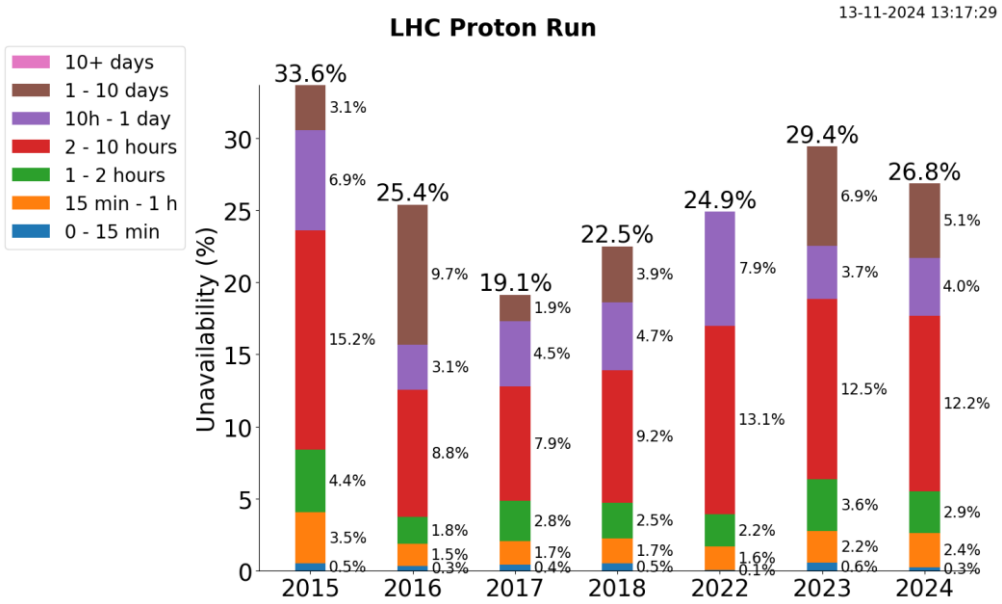
Heat load

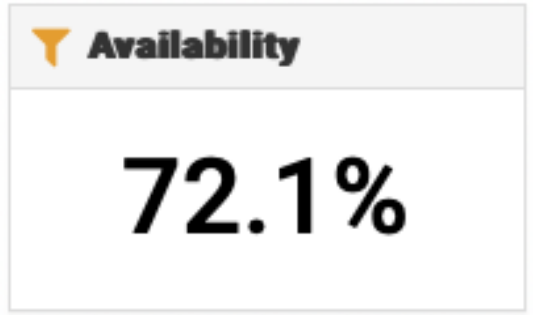
- Electron cloud induced **heat-load** mainly **limits**:
  - Train length
  - Total number of bunches
  - Bunch intensity
- After reconfiguration of cryogenic systems **operated with 25ns beam** (then BCMS) providing **better homogeneity** between bunches, beam **quality** and **operability**
- **~10% margin** gained by conditioning over 2024 (not enough for an additional full train)

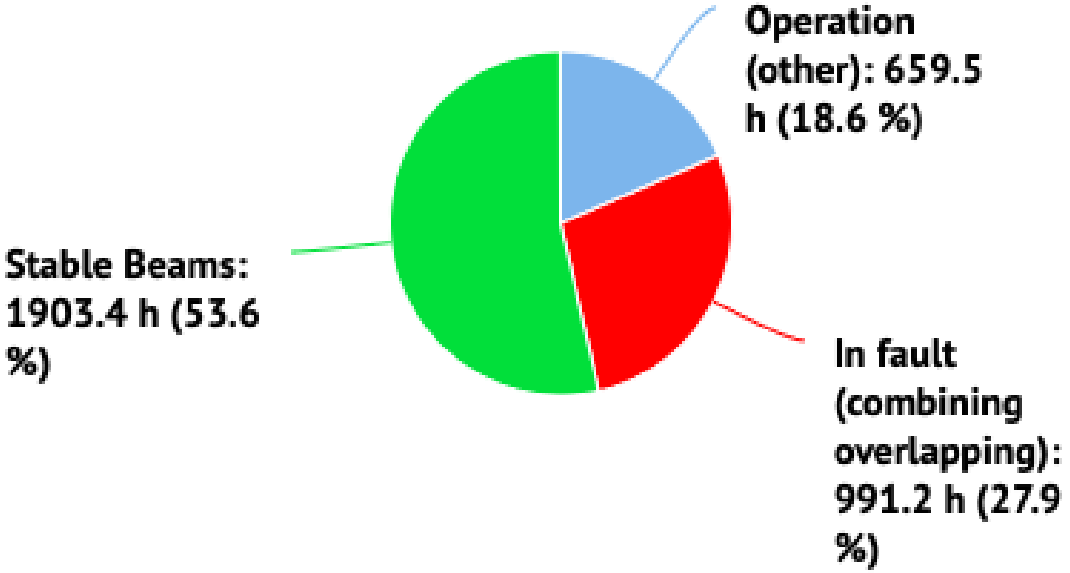


Availability

- Availability is <u>THE key factor</u> for accelerator performance
- **Availability factor** was ~constant through Run2 and Run3 for small (<24h) faults





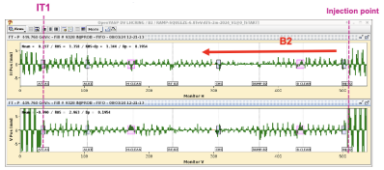


NOTE: the availability of the proton run is calculated on the effective time from the retrospetctively calculated schedule (long faults are not included)

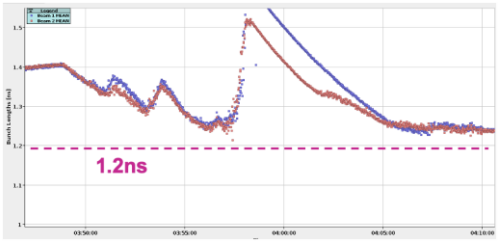
Minor differences in numbers are due to slightly different choices in term of dates (including or not scrubbing run, TS recovery etc)

LHC in 2024

First injection: 8th March (3 days early)



Bunch length control/target Limit RF module heating risk

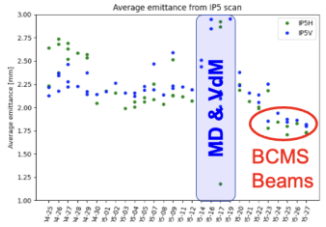


1200 bunches on 14th April (10 days early)

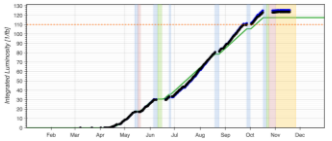
VdM & Calibration Runs, 16 – 20 May

Availability	Stable beams (SB)
85.3%	63.6%

BCMS beams May



Stable Lumi Production Summer period

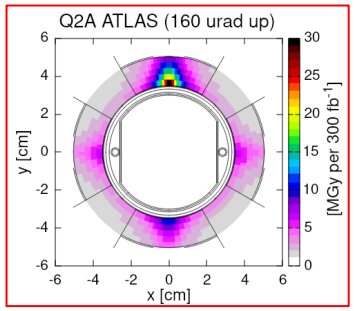


Beyond 110 fb^{-1}

pp run | ref run | IONS run

March | April | May | June | July | August | September | October | November

Reverse Polarity optics commissioned (~ +1 week)



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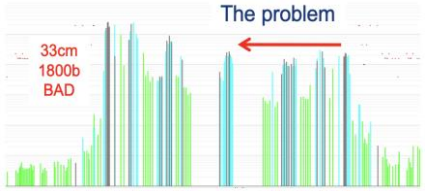
LHCb VELO closed for the 1st time

β* limited to 36 cm 17th April



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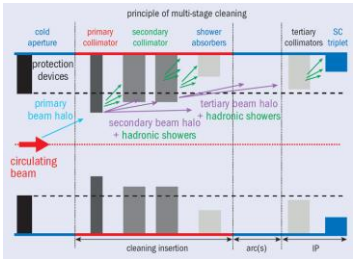
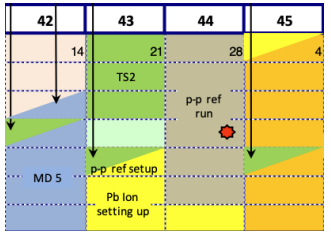
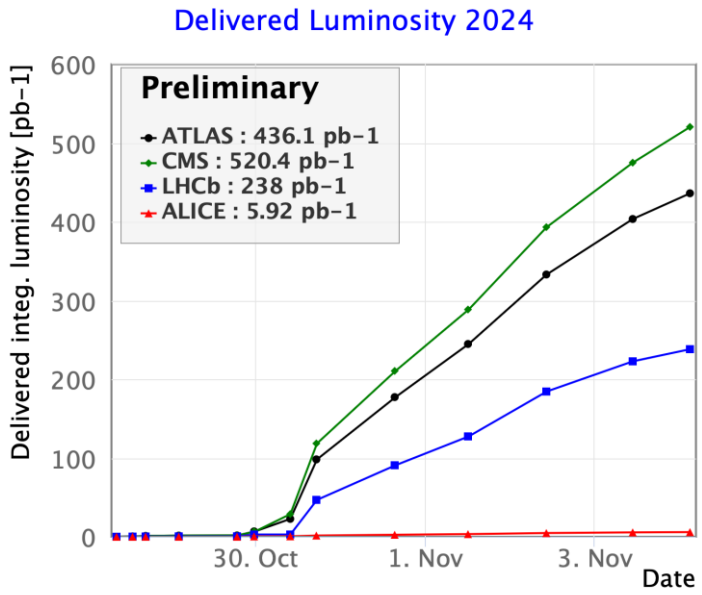
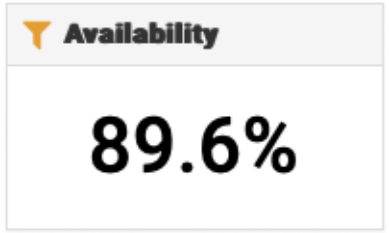


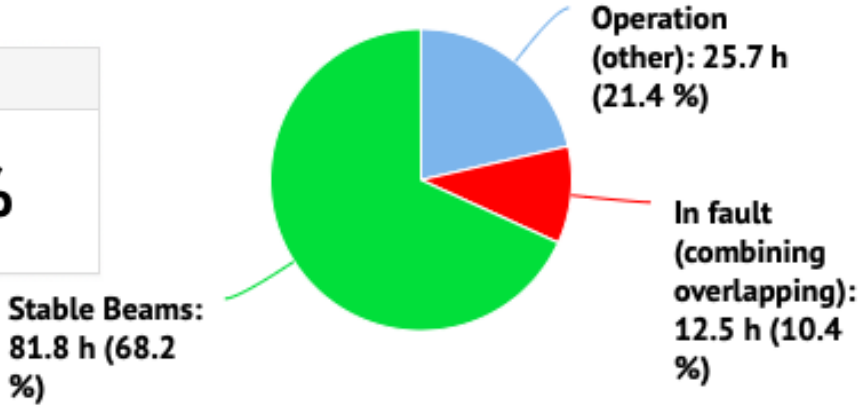
pp reference run 28th Oct – 2nd Nov



Luminosity production for pp ref run

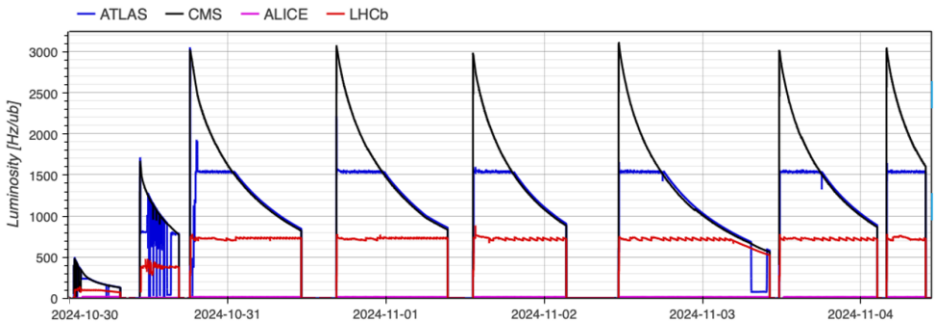






Exp	Requested lumi [pb^{-1}]	Delivered/recorded lumi [pb^{-1}]
ATLAS	350	**436 (390)**
ALICE	5.5	**5.9 (5.5)**
CMS	350	**520 (~520)**
LHCb	>100	**246 (~240)**

7-day run (extended by one day to satisfy higher targets, as a consequence of the Run3 extension), results only possible as blessed by **excellent machine availability!**



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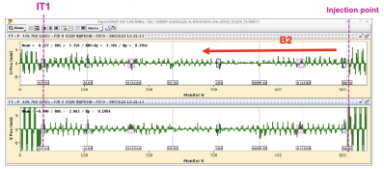

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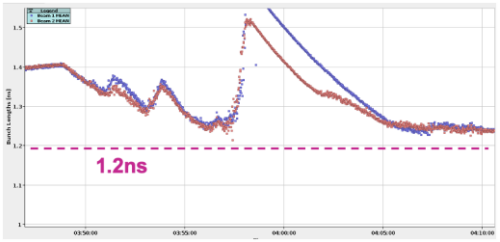

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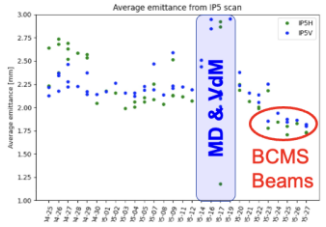

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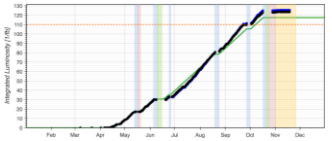


IONS run ongoing (YETS starts on 25th November)

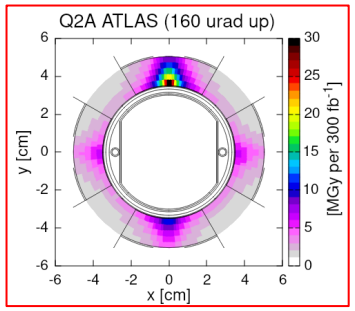
ION PHYSICS: STABLE BEAMS

Beyond 110 fb^{-1}

pp run — ref run — IONS run

March | April | May | June | July | August | September | October | November

Reverse Polarity optics commissioned (~ +1 week)



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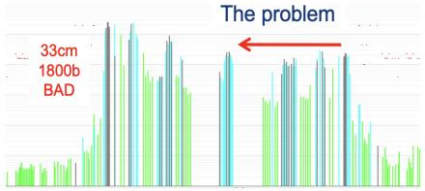

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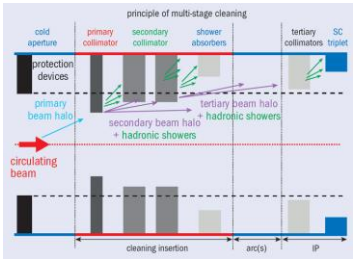

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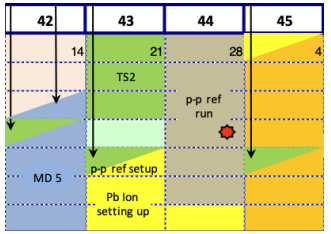


IONS run

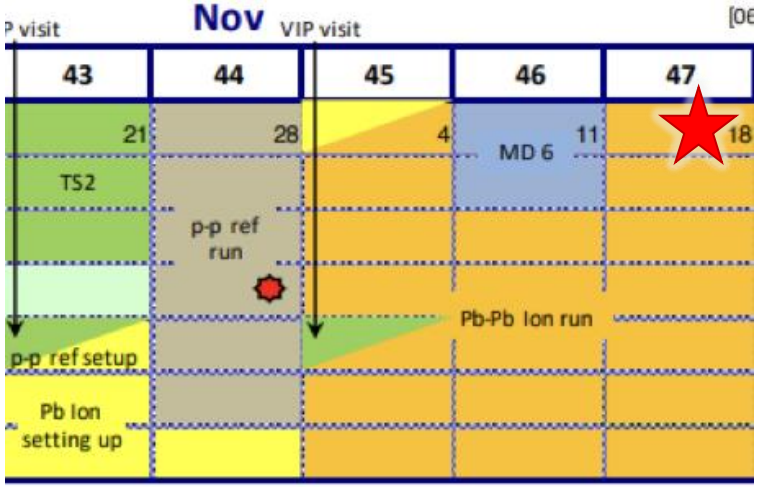
Pb-Pb physics run @**6.8 Z TeV**

- 4 days **commissioning**
  - Partially anticipated to optimize process
- 18 days **physics** (including VdM and intensity ramp-up)
- **Breaks** for VIP visit, MDs

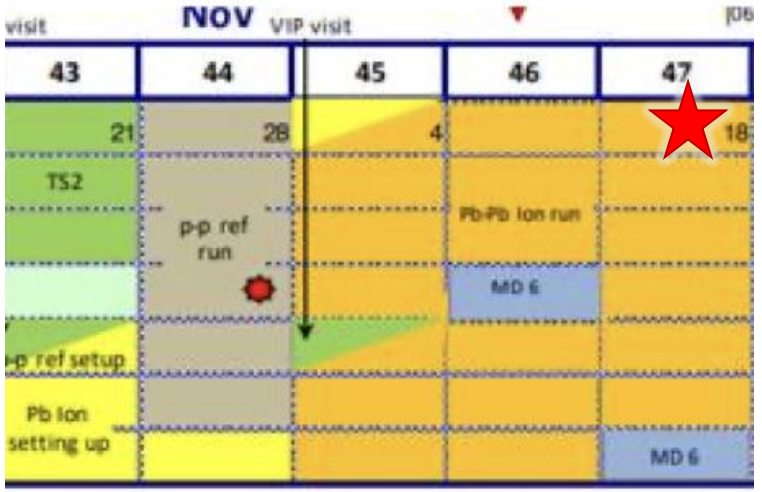
Already deployed in 2023:

- **Slip-stacking** for 50 ns beams
- **Crystals**
- **TCLD** collimators
- **BFPP orbit bump** in all IRs

v2.2



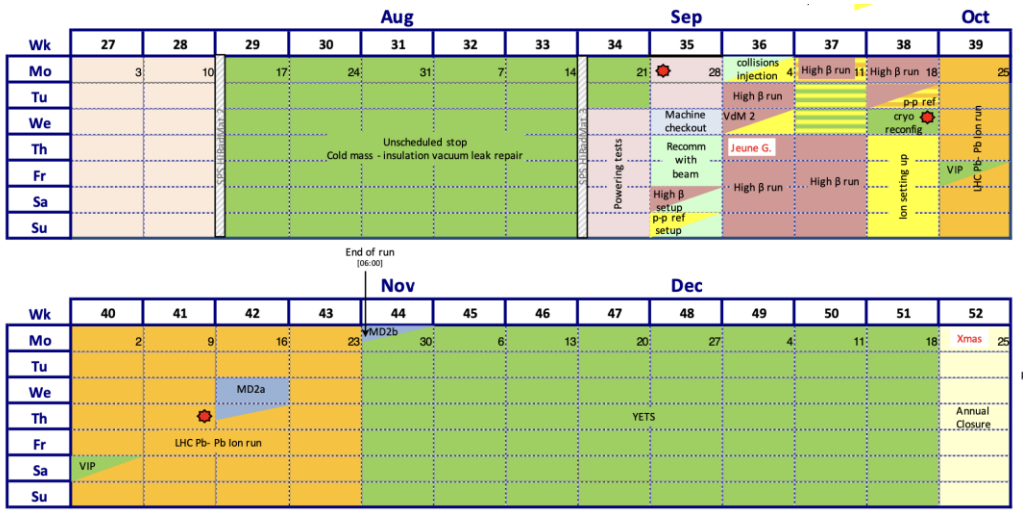
v2.3



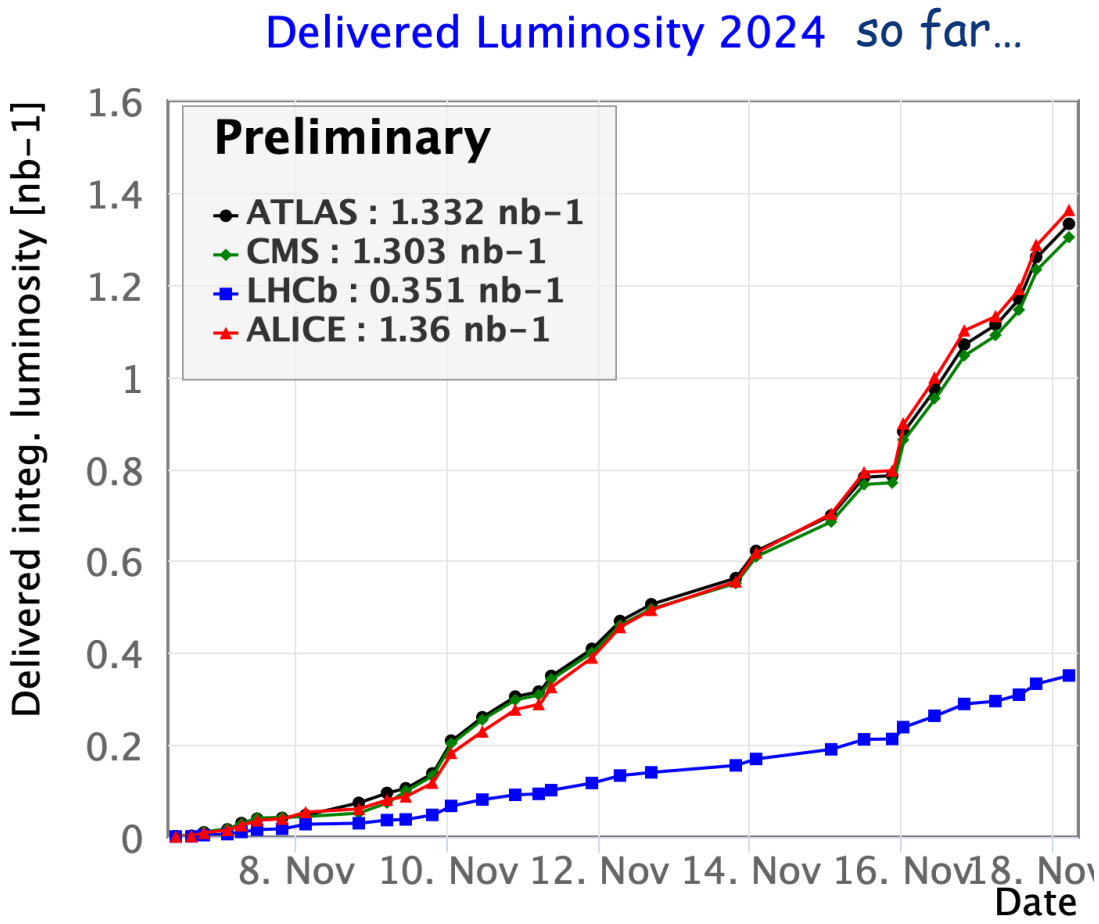
IONS run

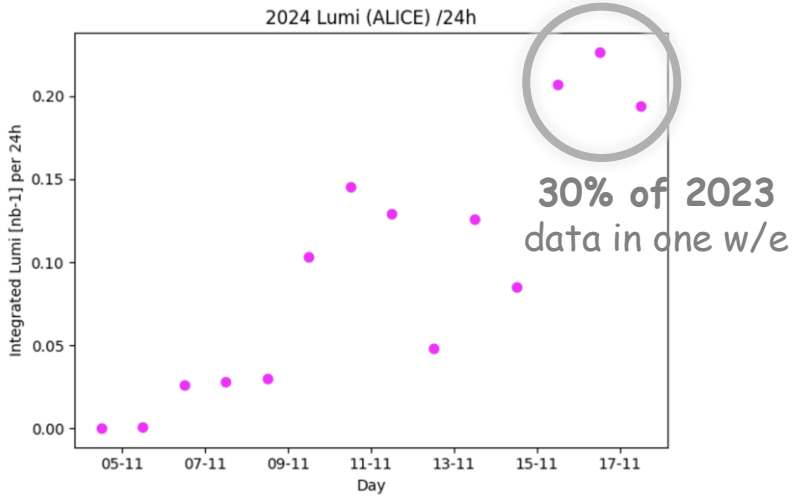
2023 run was **heavily affected** by:

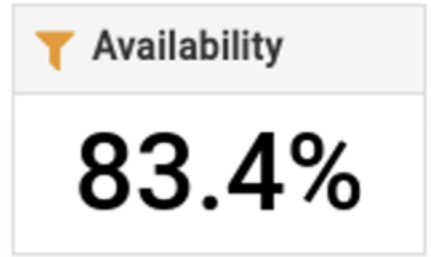
- **Radiation on Quench Protection System: beam dumps & magnet quench ➔** levelled lumi
  - Consolidation of HW with rad-tol equipment
- **10 Hz** Horizontal orbit oscillations: **beam dumps**
  - Implemented delay of cryo valve opening
- **Transverse losses** during the ramp: **beam dumps**
  - More relaxed collimator strategy
  - Squeeze partially separated from energy ramp
  - Smoother orbit corrections
- **HW goniometer** instability
  - Control system developed (automatic optimisation algorithm deployed)
- Strong **background in ALICE**
  - IP1 dispersion corrected (same as in 2023)

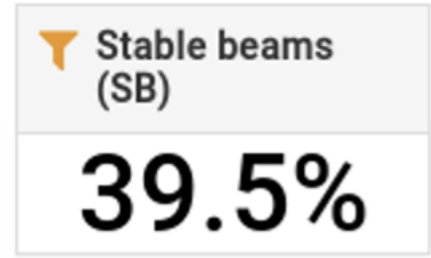


IONS run









- **Delivered luminosity** 1.36 nb^{-1}
  - 70% of 2023 overall production
- ~0.7 nb^{-1} **just over the weekend**
  - 30% of 2023 overall production
- Reached levelling at the target **instantaneous luminosity** of 6.4e^{27}, > **1h levelling in IP2**
- Injector optimisation led to **high bunch intensity at LHC** (up to ~2.2e^{8} Pb/bunch in collisions), storing up to **26.7 MJ beam** (HL design = 22 MJ)

Outline

- 2024 run highlights
  - low beta pp, pp ref run, IONS
- **2025 configuration**
- 2025 schedule options

2025/2026 configuration - introduction

- Aim at one **unique configuration** **for the rest of Run3,** to avoid commissioning overhead in 2026
- **Radiation distribution** depends on **optics choice** and **crossing angle sign**
  - Regular Xing angle sign change in IP1 was applied so far (only possible on V plane)
- There are potentially **four configurations** for each IP:
  - Nominal vs Reverse Polarity **optics**
  - H-V **crossing** angle
  - **only condition**: maintain alternated planes for Xing angles (VH or HV) in IP1 and IP5 respectively for Long Range Beam-Beam compensation (mandatory for high intensity pp physics)
- Radiation impact is particularly important for Inner Triplet and D1 magnets, as their **replacement** comes **with a VERY high cost**
- The **radiation limits** assume all of the magnet receives the same dose
  - In reality there are hot(ter) and cold(er) areas (numbers refer to hottest spot)

Proposal summary

Assumption: 100 fb^{-1} (2025) + 100 fb^{-1} (2026)
(beyond expectations (100 + 50 /fb^{-1}) in 25/26 for a total of ~530 /fb^{-1})

Proposal		Comment	IT main quads [MGy] (limit 30 MGy)		D1 [MGy] (limit 90 MGy)	
IP1	IP5		IP1	IP5	IP1	IP5
NOM-H	RP-V	• Preservation of FWD physics in P1 • PPS rotation in 2025	30.7	27.8	102.5	73
RP-H (‘25) NOM-H (‘26)	RP-V	• Partial preservation of FWD physics in P1 • PPS rotation in 2025	28.5	27.8	90.5	73
RP-H	RP-V	• Best for magnets protection • PPS rotation in 2025 • End of FWD physics program in P1	25.5	27.8	77.5	73
RP-V (‘25) RP-H (‘26)	RP-H (‘25) RP-V (‘26)	• Good for magnet protection • Minor preservation of FWD physics program in P1 • PPS rotation in 2026	28.5	31.7	77.5	73

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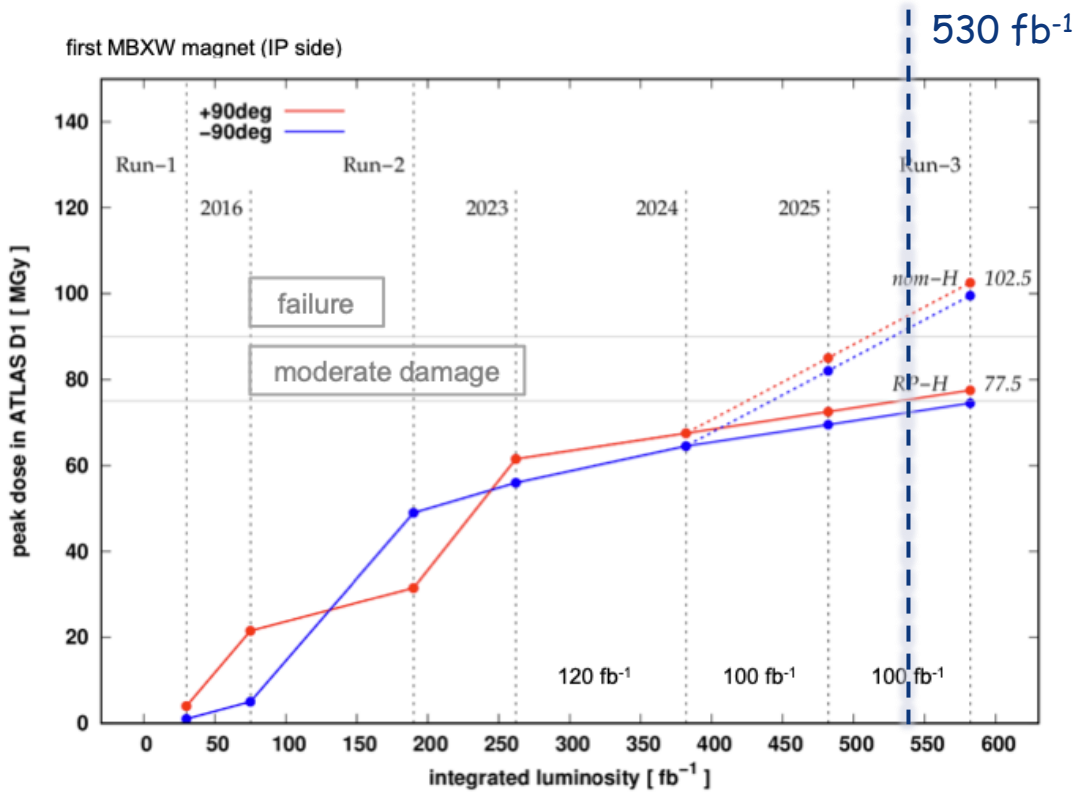
Implications

Configuration **NOM-H in P1 & RP-V in P5** has some **implications**:

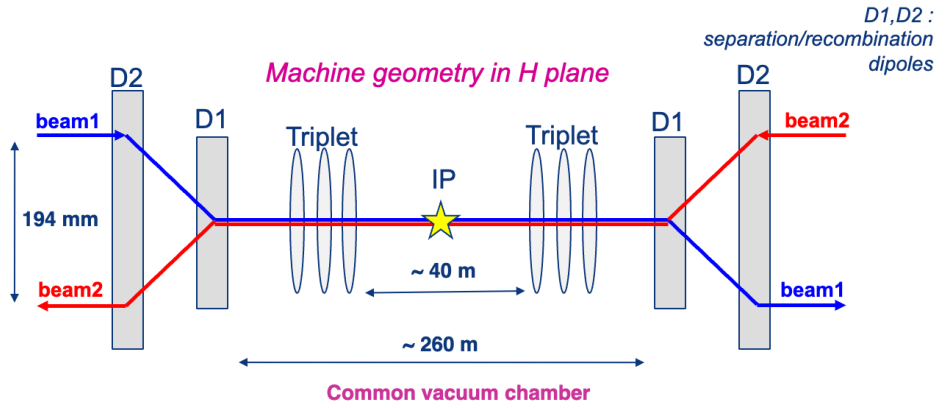
- **CT-PPS rotation** (vertical Xing angle in IP5)
- **Significant decrease** of **background** for FASER/SND
  - Simulations show lower background than in 2023
- **Preservation** of ATLAS forward physics program (**AFP**)
- Use of **flat optics**, due to inversion of Xing planes and beam screen orientation
  - already tested in MD
- **Impact on D1** non-negligible (see next slide)

RD1

- In the **Interaction Regions**, beams are combined into a **common vacuum chamber** then re-separated in the horizontal plane
- Re-establishing NOM optics in P1 will push **radiation** on D1 **beyond** the estimated damage limit
- RD1 circuits is composed of 6 **WARM magnets** per side of the IP. Failure would impact the **first modules** (possibly on both sides)
- The **risk of failure** has **to be taken seriously** and (if possible) **anticipated**
- **Options** under study:
  - Magnets replacement in YETS 25/26
  - Operation with reduced number of magnets



To be reviewed towards the end of 2025…

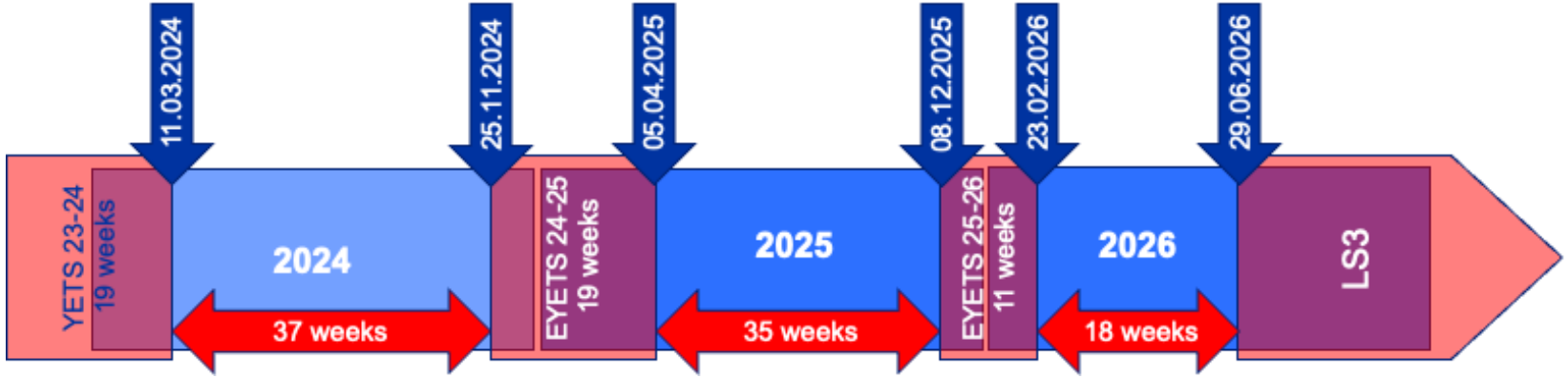


Outline

- 2024 run highlights
  - low beta pp, pp ref run, IONS
- 2025 configuration
- **2025 schedule options**

2025/2026 schedule options

- **LS3 start** shifted from 17th November 2025 to 29th June 2026
  - **Additional** p-p and Pb-Pb or perhaps p-Pb runs in 2026
  - **YETS 25-26** with minimum length of **11 weeks** – machine kept at 20 K to secure Helium inventory
  - Assumption of machine configuration change in 2025, but NOT in 2026
  - HL-LHC and CMS need **pre-LS3 cooldown** for LS3 schedule optimisation
- **Three scenarios** (A, B and C) considered – each with different Pb ion runs



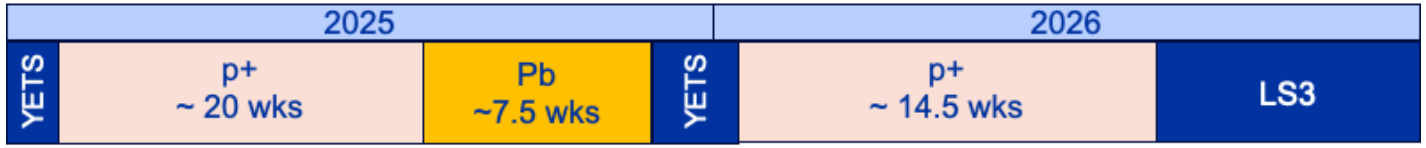
- **2025**: 35 weeks YETS to YETS
  - → 165 physics days
- **2026**: 18 weeks YETS to YETS
  - → 88 physics days

2025/2026 schedule options

Current proposal by LPC

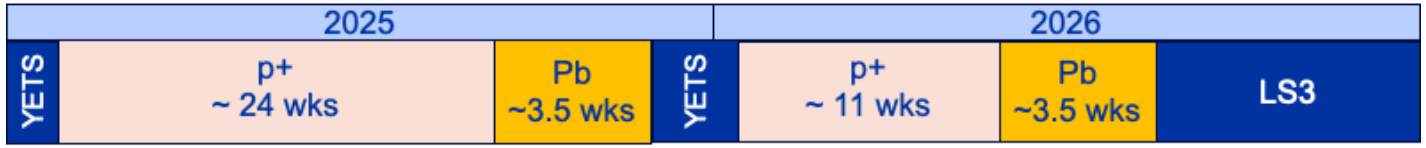
Option A

All Pb ion physics in 2025, pre-LS3 RP cooldown by low-μ run and MDs



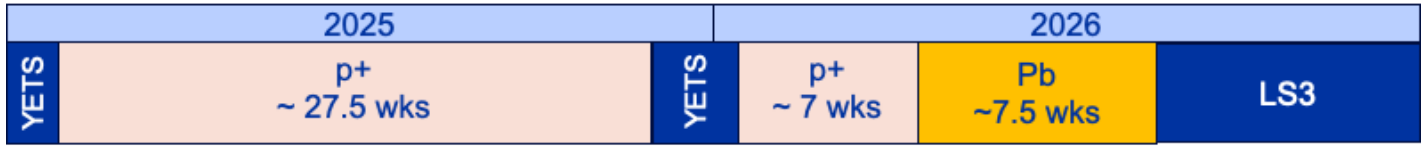
Option B

Split Pb ion run about equally – setting-up overhead ~7 days



Option C

All Pb ion physics in 2026 and 2025 cooldown by low-μ run and MDs



- **Option A** is **excluded**
  - vetoed by CMS: does not ensure sufficient pre-LS3 cooldown
- **Option B** assumed to be **most likely**
- **Option C** **not yet excluded**
  - vetoed by ALICE: risk of losing PbPb physics considered too great
  - Decision also depends on the possibility to use p-Pb running in 2026 as pre-LS3 RP cooldown

- **A and C** are **more efficient** (less setup time, more physics time)
- **B** offers a compromise between risks and cooldown

Conclusions

- **2024 Run** is (so far) very successful
  - **pp low beta:** target overpassed (best year ever for production!)
    - Best production rate, highest integrated lumi, highest beam energy stored,…
  - **pp reference:** (ambitious) expectations accomplished
  - **IONS run:** (on)going very well
- **2025/2026 machine configuration** was chosen
  - **Preservation** of forward physics
  - **Solutions** in case of magnets failure identified
- **2025/2026 schedule** options to be refined and optimized for final decision at RB

Thanks for your attention